TRACK IDENTIFICATION CODEWORDS HAVING MULTIPLE BIT ERROR CORRECTION CAPABILITY AND GENERALIZED GRAY CODE PROPERTY

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to magnetic disk drives, and more particularly, to binary codewords for identifying tracks on a rotating magnetic media in the disk drive.

Description of the Prior Art and Related Information

[0002] In order to remain competitive, disk drive manufacturers must continually provide increased data storage capacity while rigidly controlling disk drive manufacturing cost. Sampled data techniques such as partial response with maximum likelihood detection (PRML) are applied to data read from the magnetic disk to increase recording densities. Maximum likelihood detection is performed in real time using a Viterbi sequence detector. An error in the maximum likelihood detection generally causes multiple bit errors.

[0003] Existing track identification (TID) codewords may be based on a generalized Gray code that has a Hamming distance of three between adjacent TID codewords for correcting a single bit error. An example of TID codewords capable of correcting a single bit error is disclosed in U.S. Pat. No. 6,226,138 to Blaum et al. The Blaum et al patent recognizes that more than one bit error could be corrected if the Hamming distance between adjacent TID codewords could be increased. However, the Blaum et el. patent does not disclose or suggest a generalized Gray code capable of providing correction of more than a single bit error.

[0004] Accordingly, there exists a need for TID codewords that may allow correction of more than one bit error and that have the advantages of a generalized Gray code. The present invention satisfies these needs.

SUMMARY OF THE INVENTION

[0005] The present invention may be embodied in a disk drive comprising a rotating magnetic media having tracks identified by binary codewords, and in a related method. Each track codeword for a particular track within a contiguous band of tracks differs from a track codeword for an adjacent track within the contiguous band of tracks by a defined number N of bits, and differs from a track codeword for a nonadjacent track within the contiguous band of tracks by at

least the defined number N of bits. The defined number N of bits is greater than four (4) such that at least two (2) bit errors may be corrected when reading a track codeword.

[0006] In more detailed features of the invention, each track codeword may have 23 bits and the defined number N of bits may be 7 bits. Alternatively, each track codeword may have 15 bits and the defined number N of bits may be 5 bits. Also, the contiguous band of tracks may comprise between about 128 and 32,768 tracks, e.g., 2048 tracks.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The accompanying drawings illustrate embodiments of the present invention and, together with the description, serve to explain the principles of the invention.

[0008] Figure 1 is a schematic diagram of a disk drive including a rotating disk media having tracks (organized in bands) identified by binary codewords that allow correction of at least two bit errors, according to the present invention.

[0009] Figure 2 is a schematic diagram of track bands having tracks identified by binary codewords.

[0010] Figures 3A-3D show a (15, 7) codeword list for identifying tracks in a disk drive, according to the present invention.

[0011] Figure 4 is a table showing a bit comparison of two adjacent codewords from the (15, 7) codeword list of Figures 3A-3D.

[0012] Figure 5 is a table showing a bit comparison of two nonadjacent codewords from the (15, 7) codeword list of Figures 3A-3D.

[0013] Figure 6 is a table showing a bit comparison of two nonadjacent codewords from the (15, 7) codeword list of Figures 3A-3D.

[0014] Figure 7 is a table showing a bit comparison of two adjacent codewords from the (15, 7) codeword list of Figures 3A-3D.

[0015] Figure 8 shows a matrix for generating the (15, 7) codeword list of Figures 3A-3D.

[0016] Figure 9 shows a Hadamard matrix of order 8 related to the generating matrix of Figure 8.

[0017] Figure 10 shows a matrix for generating a (23, 11) codeword list for identifying tracks in a disk drive, according to the present invention.

[0018] Figure 11 shows a first Hadamard matrix of order 12 related to the generating matrix of Figure 10.

[0019] Figure 12 shows a second Hadamard matrix of order 12.

[0020] Figure 13 is a table showing a bit comparison of two adjacent codewords from the (23, 11) codeword list of Figures 17A-17PP.

[0021] Figure 14 is a table showing a bit comparison of two nonadjacent codewords from the (23, 11) codeword list of Figures 17A-17PP.

[0022] Figure 15 is a table showing a bit comparison of two nonadjacent codewords from the (23, 11) codeword list of Figures 17A-17PP.

[0023] Figure 16 is a table showing a bit comparison of two adjacent codewords from the (23, 11) codeword list of Figures 17A-17PP.

[0024] Figures 17A-17PP show a (23, 11) codeword list for identifying tracks in a disk drive, according to the present invention.

[0025] Figure 18 shows a Hadamard matrix of order 16.

DETAILED DESCRIPTION

[0026] With reference to Figures 1-3D, the present invention may be embodied in a disk drive 10 comprising a rotating magnetic disk media 12 having tracks 14 identified by binary codewords CW, and in a related method. Each track codeword for a particular track within a contiguous band B of tracks differs from a track codeword for an adjacent track within the contiguous band of tracks by a defined number N of bits, and differs from a track codeword for a nonadjacent track within the contiguous band of tracks by at least the defined number N of bits. The defined number N of bits is greater than four (4) such that at least two (2) bit errors may be corrected when reading a track codeword.

[0027] The number of bit differences between the codewords CW is often referred to as the Hamming distance D. The codeword lists shown in Figures 3A-3D and in 17A-17PP have a generalized Gray code property of a fixed number N of bit transitions (or a fixed distance) between each adjacent codeword. In addition, each codeword in the list has a distance of at least N with each nonadjacent code word. These codeword distance properties are particularly advantageous for encoding track identification TID numbers in a disk drive 10.

[0028] The disk media 12 generally has more tracks 14 than numbers available in the codeword lists. Accordingly, the codewords CW are repeated in contiguous track bands B1-BL. A head position is read each time the disk drive's read head encounters a servo sector. The disk drive's control system, based on the physical motion limits of the head across the disk media between

servo sector reads, can predict from which band or adjacent bands to expect the next head position read.

[0029] With particular reference to Figure 3A-3D, the (15, 7) codeword list has 15-bit codewords CW generated from 7-bit TID numbers. Thus, the (15, 7) codeword list has 128 unique codewords. The (15, 7) codeword distance properties are shown with reference to Figures 4-7. Figure 4 shows a comparison between two adjacent codewords for the TID numbers 19 and 20. The codewords for 19 and 20 have a bit difference N of 5 bits so the codewords have a distance D of 5. Figure 5 shows a comparison between two nonadjacent codewords for the TID numbers 19 and 21. The codewords for 19 and 21 have a distance D of 6 which is greater than the adjacent codeword bit difference N of 5. Similarly, Figure 6 shows a comparison between two nonadjacent codewords for the TID numbers 19 and 94. The codewords for 19 and 94 have distance D of 9. Figure 7 shows a comparison between two adjacent codewords for the TID numbers 93 and 94. The codewords for 93 and 94 have a distance D of 5, again confirming the adjacent codeword bit difference N of 5.

[0030] The (15, 7) codeword list may be generated by first converting the TID numbers to Gray code U. A generating matrix G7, shown in Figure 8, is defined according to the equation $G = [I1 | P]$, where I1 is an identity matrix of dimensions (K, K), and where P is a submatrix (of a Hadamard matrix) of dimension (K, M-K). K is the number of bits for the TID number and M is the number of bits for the codeword. In this example, K is equal to 7 and M is equal to 15. Figure 9 shows a normalized Hadamard matrix of order 8. The matrix P is selected from the last 7 rows of the normalized Hadamard matrix. A binary representation of the Hadamard matrix is generated by replacing each instance of "-1" with "0". The codeword list V is generated by modulo 2 matrix multiplication in accordance with the equation: $V = U * G$. This matrix multiplication can be readily performed with the assistance of software having matrix multiplication facilities such as MathLab or SciLab. Because the generating matrix G7 includes the identity matrix in the first 7 columns, the first 7 columns of the (15, 7) codeword list merely repeats the corresponding input Gray code U. The codewords also may be decoded according to the equation: $U = V * F$, where F is a matrix defined by the equation $F = [P^T | I2]$, where P^T is the transform of the matrix P above, and I2 is an identity matrix of dimensions (M-K, M-K).

[0031] During operation, a codeword is read at each servo sector. An error in the read value can be decoded in using a table. The table may list all valid codewords and a majority vote used to

determine the closest codeword. Alternatively, the table may list all possible read values which are pre-assigned a closest TID number. The value read from the servo sector is decoded by looking up the value in the table to find the corresponding TID number. Also, algebraic decoding and soft-position decoding may be used. The disk drive 10 generally includes volatile and nonvolatile memory and at least one internal microprocessor. The program code and data tables for implementing the decoding techniques may be stored in the nonvolatile memory and transferred to volatile random access memory (RAM) for execution by the microprocessor.

[0032] Figure 10 shows a generating matrix G11 for generating the (23, 11) codeword list shown in Figures 17A-17PP. The generating matrix is based on a first normalized Hadamard matrix H12A of order 12, shown in Figure 11. The (23, 11) codeword list has 2048 unique codeword values. The (23, 11) codeword distance properties are shown with reference to Figures 13-16. Figure 13 shows a comparison between two adjacent codewords for the TID numbers 49 and 50. The codewords for 49 and 50 have a bit difference N of 7 bits so the codewords have a distance D of 7. Figure 14 shows a comparison between two nonadjacent codewords for the TID numbers 49 and 51. The codewords for 49 and 51 have a distance D of 8 which is greater than the adjacent codeword bit difference N of 7. Similarly, Figure 15 shows a comparison between two nonadjacent codewords for the TID numbers 49 and 1984. The codewords for 49 and 1984 have distance D of 7, with is equal to the adjacent difference N of 7. Figure 16 shows a comparison between two adjacent codewords for the TID numbers 1983 and 1984. The codewords for 1983 and 1984 have a distance D of 7, again confirming the adjacent codeword bit difference N of 7. The codeword bit difference N of 7 may allow correction of 3 bit errors.

[0033] A (23, 11) codeword list having similar properties may be generated based on a second normalized Hadamard matrix H12B of order 12, shown in Figure 12. Although the bit patterns of the resulting (23, 11) codeword list may differ, the distance properties of adjacent and nonadjacent codewords may remain the same. Similarly, a (31, 15) codeword list may be generated based on a normalized Hadamard matrix H16 of order 16, shown in Figure 18. The resulting (31, 15) codeword list may have distance properties of adjacent and nonadjacent codewords that allow that correction of at least two bit errors read when the read head passes over a servo sector to read a track codeword. The (31, 15) codeword list has 32,768 unique codeword values.